

Reconstruction of $f(G)$ gravity with ordinary and entropy-corrected (m, n) type Holographic dark energy model

Rahul Ghosh^{1,*} and Ujjal Debnath^{2,†}

¹ *Department of Mathematics, Bhairab Ganguly College, Kolkata-700 056, India.*

² *Department of Mathematics, Bengal Engineering and Science University, Shibpur, Howrah-711103, India*

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We have discussed the correspondence of the well-accepted $f(G)$ gravity theory with two dark energy models : (m, n) -type holographic dark energy [(m, n) -type HDE] and entropy-corrected (m, n) -type holographic dark energy. For this purpose, we have considered the power law form of the scale factor $a(t) = a_0 t^p, p > 1$. The reconstructed $f(G)$ in these models have been found and the models in both cases are found to be realistic. We have also discussed the classical stability issues in both models. The (m, n) -type HDE and its entropy-corrected versions are more stable than the ordinary HDE model.

I. INTRODUCTION

The recent observational data from Ia supernovae, the large scale structure and cosmic microwave background anisotropies confirm that the universe is undergoing a late-time acceleration [1–11]. A unknown component, known as dark energy, is believed to be responsible for this accelerated expansion. Cosmological observation suggest that the two-thirds of the the total energy of the universe is been occupied by this dark energy. Remaining portion is almost occupied by dark matter with a little presence of baryonic matter [12].

There are many candidates for dark energy and the simplest among them is a tiny positive cosmological constant with equation of state parameter $\omega = -1$. But the fine-tuning and the cosmological coincidence problem occur when we deal with the cosmological constant. Hence we tend to look at the dynamic scalar field models whose equation of state parameter are not constant but evolve with the cosmic time. The modified gravity approach is a gravitational alternative to explain the accelerated expansion. These two approaches may compliment each other as shown by the works of many authors [13–29].

*Electronic address: ghoshrahul3@gmail.com

†Electronic address: ujjaldebnath@gmail.com

Holographic principle proposed by Fischler and Susskind [30] is one of the important results of the recent investigations that arise exploring the quantum gravity theory or the string theory [31, 32]. Depending on this holographic principle the nature of the dark energy in the context of quantum gravity is called the holographic dark energy (HDE). An enlargement relationship as proposed by *Cohen et al* [33] between the infra-red (IR) and ultraviolet cut-offs due to the limitation set by the formation of a black-hole, which establishes an upper limit for the vacuum energy, $L^3 \rho_v \leq LM_P^2$, where ρ_v is the HDE density related to the UV cut-off, L is the IR cut-off and M_P is the reduced Planck mass. The HDE may provide simultaneously natural solutions to both dark energy and cosmological problems [34]. Specially it can resolve the coincidence problem [35] and the phantom crossing [36]. Besides the model has reasonable agreement with the astrophysical data of CMB, SNeIa and galaxy redshift surveys [37]. On these accounts, HDE paradigm has been extended via different cut-offs [38] and entropy corrections [39]. The holographic scale L can be identified with the future event horizon [34], the conformal age of the universe [40] or the Ricci scalar of the universe [41]. Specially the model taking the conformal age of the universe is also dubbed as new agegraphic dark energy model. A recent extension of this idea is (m, n) -type HDE [42], where m and n are the parameters associated with the chosen IR cut-off

$$L = \frac{1}{a^m(t)} \int_0^t a^n(t') dt' \quad (1)$$

A holographic dark energy model with a conformal-like age of the universe as the scale L [43] is consistent with the history from the inflation to the current universe. In this sense, all such scales are proposed at a phenomenological level. In analogy with the trend, perhaps the direct physical motivation of proposing such characteristic scales for (m, n) -type holographic dark energy model is still obscure, but it generalized the theory with significant improvements and the parameters (m, n) provide us more space in theory to fit the observational data. In particular, for some specific values of (m, n) the equation of state can naturally evolve cross phantom divide even without introducing an interaction between dark energy and dark matter. Also when (m, n) take some specific value all the agegraphic-like dark energy models can be recovered. This construction is also applicable to the models with generalized future event horizon as the holographic size in the same spirit. For age-like holographic models, when $m = n$ it seems that dark energy has the same behavior as the dominant ingredient in the early epoches of the universe. Which imply that dark energy might be unified with dark matter. However, we have to introduce some mechanism to make dark energy deviate from dark matter state, and eventually become dominant and be responsible for the acceleration of the universe. To achieve this we need some appropriate

interactions between dark energy and dark matter. This model is always stable in the dark energy dominated era in Newtonian gauge. The preliminary numerical analysis has indicated that this model fits with the observational data very well. The best-fit analysis in this reference indicates that this model with $m = n + 1$ and small m is more favored including the cases of $(m, n) = (1, 0), (2, 1), (3, 2), (4, 3)$ etc [44].

Black-hole entropy (BH) S_{BH} plays an important role in the derivation of HDE. It is well-known that $S_{BH} = \frac{A}{4G}$, where $A(\sim L^2)$ is the area of the BH horizon. The BH entropy-area relation faces a modification in loop quantum gravity (LQG) due to thermal equilibrium fluctuation, quantum fluctuation or mass and charge fluctuations, in the form [45–47] $S_{BH} = \frac{A}{4G} + \xi \log \frac{A}{4G} + \zeta$, where ξ and ζ are dimensionless constants of unit order. Wei [48] has proposed the energy-density of the entropy-corrected HDE with the help of this corrected entropy-area relation setup of LQG and obtained the energy density of the entropy-corrected HDE. The application of the the IR cut-off $L = \frac{1}{a^m(t)} \int_0^t a^n(t') dt'$ here would be a interesting aspect to see.

Modification of the Einstein's general theory of relativity is popular aspect to explain the the accelerated cosmic expansion. $f(R)$ gravity [49–51], $f(T)$ gravity [52, 53], $f(G)$ gravity [54], $f(R, T)$ gravity, $f(R, G)$ gravity are some popular modified gravity models. Beside explaining cosmic expansion these theories are also helpful in explaining the unification of early-time inflation and late-time acceleration era and then the non-phantom to phantom phase and many more. There are many works in the literature on the correspondence between different kinds of HDE and modified gravity [26, 27, 55–59]. In this work, we have considered the correspondence of $f(G)$ gravity (where G is the Gauss-Bonnet invariant) with ordinary and entropy-corrected (m, n) -type HDE in the light of power law of $a(t)$.

The Einstein's field equations in FRW model in the background of $f(G)$ gravity are discussed in section II. Our main aim is to discuss the correspondence of the well-accepted $f(G)$ gravity theory with two dark energy models : (m, n) -type holographic dark energy [(m, n) -type HDE] and entropy-corrected (m, n) -type holographic dark energy, which will be discussed in sections IIA and IIB. We have also discussed the classical stability issues in both models in section III. Finally, we draw some concluding remarks.

II. RECONSTRUCTION OF $F(G)$ GRAVITY

The action of $f(G)$ is considered as [60]

$$S = \int d^4x \sqrt{-g} \left(\frac{1}{2} R + f(G) + \mathcal{L}_m \right) \quad (2)$$

where, $f(G)$ is an arbitrary function of Gauss-Bonnet invariant G , $G = R_{\alpha\beta\gamma\delta}R^{\alpha\beta\gamma\delta} - 4R_{\alpha\beta}R^{\alpha\beta} + R^2$, and \mathcal{L}_m is Lagrangian of the matter present in the universe. This action describes the Einstein's gravity coupled with perfect fluid plus a Gauss-Bonnet (G) term. We set the Planck mass to unity. The field equations in FLRW space-time with signature $(-, +, +, +)$ are

$$3H^2 = -24H^3\dot{f}_G + Gf_G - f + \rho_m = \rho_{eff} \quad (3)$$

$$-2\dot{H} = -8H^3\dot{f}_G + 16H\dot{H}\dot{f}_G + 8H^2\ddot{f}_G + \rho_m = \rho_{eff} + p_{eff} \quad (4)$$

where $-24H^3\dot{f}_G + Gf_G - f$ is the energy density contribution of $f(G)$, further ρ_{eff} and p_{eff} are the effective energy density and pressure respectively. Here $G = 24H^2(\dot{H} + H^2)$, $H = \frac{\dot{a}}{a}$, where the dot represents the time derivative. Now, further calculation reveals that $\rho_m = \rho_0 a^{-3(1+\omega)}$, where ρ_0 is the matter density at redshift $z = 0$ and ω is EoS parameter of the matter field.

In literature, there is no unique functional form of $f(G)$, but to study the evolution, a functional form of $f(G)$ is required. Now to reconstruct $f(G)$ gravity model we are trying to consider two models (i) (m, n) -type HDE Model and (ii) entropy-corrected (m, n) -type HDE Model.

A. Reconstruction with (m, n) -type HDE Model

Now to process to reconstruct $f(G)$ gravity with (m, n) -type HDE, we need the energy density, which is given by [42]

$$\rho_v = \frac{3b^2}{L^2} \quad (5)$$

with $b = \text{constant}$ and $L = \text{generalized IR cut-off defined as}$

$$L = \frac{1}{a^m(t)} \int_0^t a^n(t') dt' \quad (6)$$

where m and n are constants. This model mimics the general agegraphic Dark energy models with some differences. The naive difference backs to the choice of appropriate cut-off of the model. Also for some reasonable values of (m, n) this model crosses the phantom line $\omega = -1$. Also the pair (m, n) are arbitrary and at level of phenomenological the high energy models, need not to be

integers. This model generates ordinary HDE for $m = n = 1$. The new agegraphic corresponds to $(m = 0, n = 1)$. Finally in favour of the observational data, the pair $(m, n) = (0, 1)$ and $(m, n) = (4, 3)$ are compatible.

Simple calculation reveals that

$$\dot{L} = -mHL + a^{n-m}(t) \quad (7)$$

Now to establish the required correspondence we set $\rho_v = \rho_G$. It gives

$$-24H^3\dot{G}f_{GG} + Gf_G - f(G) = \frac{b^2}{L^2} \left[\frac{2a^{n-m}(t)}{HL} - 2m - 3 \right] \quad (8)$$

where f_G, f_{GG} are 1st and 2nd order derivatives of $f(G)$ with respect to G . Now by simple power law representation $a(t) = a_0 t^p$, where $a_0 > 0$ and $p >$ are constants we have the IR cut-off $L = \frac{a_0^{n-m}}{pn+1} t^{p(n-m)+1}$, $G = \frac{24(p-1)p^3}{t^4}$. Putting these in (7) and calculating further we get the equation in terms of G as

$$AG^2 f_{GG} - Gf_G + f + BG^{\frac{p(n-m)+1}{2}} = 0 \quad (9)$$

where

$$A = \frac{4}{p-1} \quad (10)$$

$$B = a_0^{2(m-n)} b^2 (1+np)^2 \left\{ -3 - 2m + \frac{2(1+pn)}{p} \right\} 24p^3 (p-1)^{2p(m-n)-2} \quad (11)$$

which is a second order differential equation with solution

$$f(G) = \alpha G^{\frac{1-mp+np}{2}} + c_1 G^{\frac{1}{A}} + c_2 G \quad (12)$$

where c_1 and c_2 are arbitrary integration constants and

$$\alpha = \frac{4B}{(1+mp-np)(-2-A+Am p-An p)} \quad (13)$$

Now we can see that this $f(G)$ increases with G and it forms a realistic model as in this case $f(G) \rightarrow 0$ as $G \rightarrow 0$ [54]. In figure 1, we have drawn the $f(G)$ against G for some particular values of p , which shows the ever increasing with positivity nature of $f(G)$ as G increases.

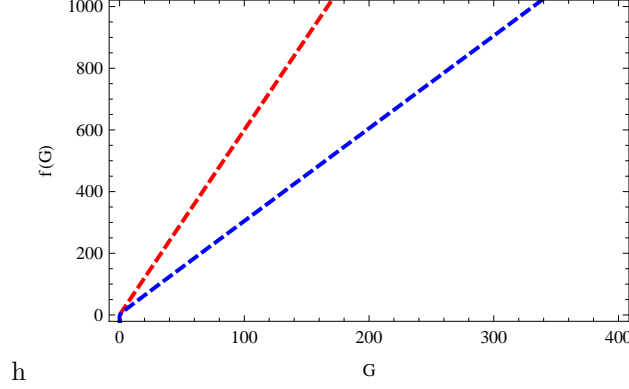


FIG. 1: Evolution of (m, n) -type HDE $f(G)$ model versus G with power law scale factor, the Red and Blue lines are associated with non-zero values of m, n and $p = 10$ and $p = 2$ respectively.

B. Reconstruction with entropy-corrected (m, n) -type HDE Model

Considering the corrected entropy-are relation with derivation of HDE, we can obtain the energy density of the entropy-corrected (m, n) -type HDE as

$$\rho_V = \frac{3c^2}{L^2} + \frac{\xi}{L^4} \log L^2 + \frac{\zeta}{L^4} \quad (14)$$

with c, ξ, ζ as dimensionless constants and IR cut-off as considered in equation (5). Again to reconstruct $f(G)$ with this dark energy we have considered $\rho_G = \rho_v$, which yields

$$\frac{3c^2}{L^2} + \frac{\xi}{L^4} \log L^2 + \frac{\zeta}{L^4} = -24H^3 \dot{f}_G + Gf_G - f \quad (15)$$

after considering the power law scale factor $a(t) = a_0 t^p$, with $a_0 > 0$ and $p > 1$ constants we can simply discover the equation (14) as

$$AG^2 f_{GG} - Gf_G + f + BG^{\frac{pn-pm+1}{2}} + G^{pn-pm+1}(C + D \log G) = 0 \quad (16)$$

where

$$A = \frac{4}{1-p} \quad (17)$$

$$B = 3a_0^{2(m-n)} c^2 (1+pn)^2 [24(p-1)p^3]^{\frac{pm-pn+1}{2}} \quad (18)$$

$$C = a_0^{4(m-n)} (1+pn)^4 [24(p-1)p^3]^{pm-pn-1} \left[\zeta + \xi \log \left\{ \frac{a_0^{2(n-m)}}{(1+pn)^2} 24(p-1)p^3 \right\}^{\frac{pn-pm+1}{2}} \right] \quad (19)$$

$$D = -\frac{1}{2} a_0^{4(m-n)} (1+pn)^4 [24p^3(p-1)]^{pm-pn-1} \xi^{pn-pm+1} \quad (20)$$

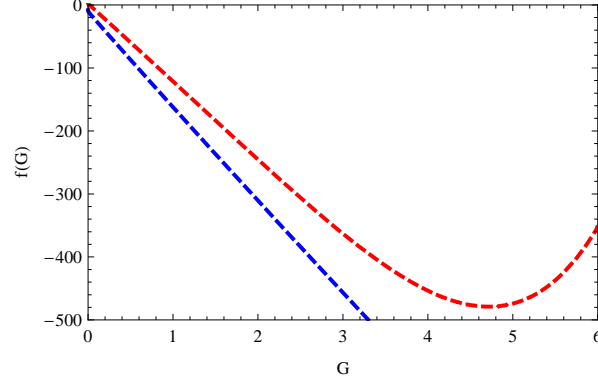


FIG. 2: Evolution of entropy-corrected (m, n) -type HDE $f(G)$ model versus G with power law scale factor, the Red and Blue lines are associated with non-zero values of $m = 1.3, n = 3, p = 2.06$ and $m = 0, n = 1, p = 2$ respectively.

which produces $f(G)$ in the form

$$f(G) = \alpha(c_1 G^{\frac{1}{A}} + c_2 G) + \beta G^{\frac{1-pm+pn}{2}} + G^{1-pm+pn}(\gamma - \delta \log G) \quad (21)$$

where

$$\tau = (m - n)^2 p^2 [1 + pm - pn(-1 + A - Apm + Apn)^2 \{2 + A(-1 + pm - pn)\}] \quad (22)$$

$$\alpha = \frac{1}{\tau} (m - n)^2 p (1 + pm - pn) \{1 + A(-1 + pm - pn)\}^2 \{2 + A(-1 + pm - pn)\} \quad (23)$$

$$\beta = \frac{1}{\tau} [-4B(m - n)^2 p^2 (-1 + A - Apm + Apn)^2] \quad (24)$$

$$\gamma = \frac{1}{\tau} [(A-1)\{D+C(m-n)\} - A\{2D+C(m-n)\}(m-n)p(-1-pm+pn)(-2+A-Apm+Apn)] \quad (25)$$

$$\delta = \frac{1}{\tau} D(m - n)p(1 + pm - pn)[2 + A(-1 + pm - pn)\{3 + A(-1 + pm - pn)\}] \quad (26)$$

and c_1 and c_2 are arbitrary constants.

We can clearly see by figure 2 that $f(G)$ is a decreasing function of G and $f(G) \rightarrow 0$ as $G \rightarrow 0$, which reveals that it is a realistic model.

III. STABILITY ANALYSIS

Squared speed of sound $v_s^2 = \frac{\dot{p}}{\dot{\rho}}$ is an important quantity to test the stability of the background evolution. Positive value of v_s^2 implies classical stability of a given perturbation [61, 63]. Interacting

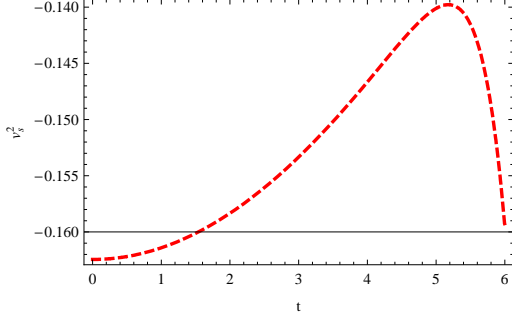


FIG. 3: This figure plots v_s^2 versus t for (m,n) -type HDE $f(G)$ model and we find that it gives classical instability for $m = 0, n = 1$

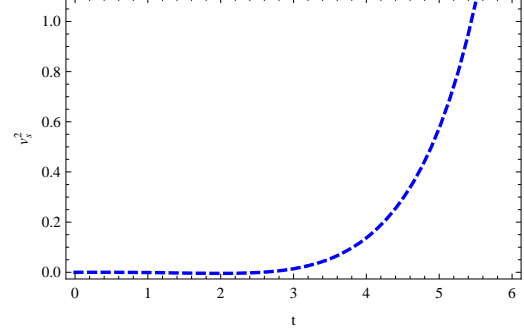


FIG. 4: This figure plots v_s^2 versus t for (m,n) -type HDE $f(G)$ model and we find that it gives classical stability for $m = 4, n = 3$

new HDE is characterized by negative v_s^2 giving classical instability by Sharif et al [61]. Myung [62] testified that squared speed for HDE always stays at negative level for choosing future event horizon as IR cut-off, while for those for Chaplygin gas and tachyon it stays non-negative. Kim et al [63] observed that the perfect fluid for agegraphic dark energy is classically unstable as v_s^2 is always negative and Jawad et al [26] shows that $f(G)$ model in HDE scenario with power law scale factor is classically unstable.

We here considered the v_s^2 as equal to $\frac{\dot{p}_{eff}}{\rho_{eff}}$ and plot this v_s^2 verses the cosmic time t for both reconstructions of $f(G)$ models. For the (m,n) -type HDE $f(G)$ model with power law scale factor, the model is classically unstable for $m = 0, n = 1$ (figure 3) and is stable for $m = 4, n = 3$ (figure 4). And for the entropy-corrected (m,n) -type HDE $f(G)$ model, the model is stable for both $m = 0, n = 1$ (figure 5) and $m = 1, n = 3$ (figure 6).

IV. CONCLUDING REMARKS

In this work, we have considered the generalized version of holographic dark energy (HDE) like (m,n) type HDE model in the background of $f(G)$ gravity in FRW universe. We have discussed the correspondence of the well-accepted $f(G)$ gravity theory with two dark energy models: (m,n) -type holographic dark energy [(m,n) -type HDE] and entropy-corrected (m,n) -type holographic dark energy. Here we have considered the power law form of the scale factor $a(t) = a_0 t^p, p > 1$. With this choice, the explicit forms of $f(G)$ have been found in terms of G for both models. The model in both cases are found to be realistic i.e., $f(G) \rightarrow 0$ as $G \rightarrow 0$. In figures 1 and 2, we have shown that $f(G)$ decreases with G from positive side for (m,n) -type

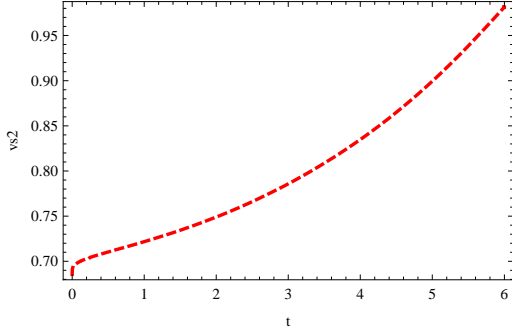


FIG. 5: This figure plots v_s^2 versus t for entropy-corrected (m,n) -type HDE $f(G)$ model and we find that it gives classical stability for $m = 0, n = 1$

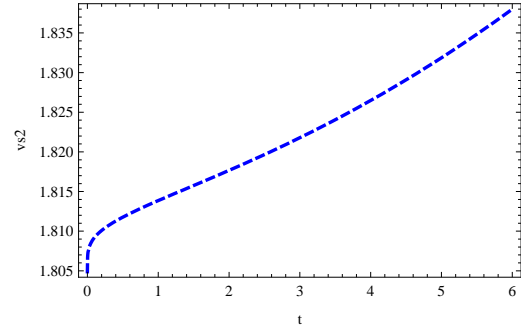


FIG. 6: This figure plots v_s^2 versus t for entropy-corrected (m,n) -type HDE $f(G)$ model and we find that it gives classical stability for $m = 1, n = 3$

HDE and from negative side for entropy-corrected (m,n) -type HDE. We have also discussed the classical stability issues in both models with the condition that $v_s^2 > 0$ for these reconstructed models. For (m,n) -type HDE model, v_s^2 has been drawn in figures 3 and 4 for $(m,n) = (0,1)$ and $(m,n) = (4,3)$. For $(m,n) = (0,1)$, we see that $v_s^2 < 0$, which is unstable but for $(m,n) = (4,3)$, we see that $v_s^2 > 0$, which is classically stable. So we conclude that (m,n) type HDE is more stable model than ordinary HDE model in $f(G)$ gravity. Also for entropy-corrected (m,n) -type HDE model, v_s^2 has been drawn in figures 3 and 4 for $(m,n) = (0,1)$ and $(m,n) = (1,3)$. For both the cases, we observe that $v_s^2 > 0$. So entropy-corrected model is classically stable for both ordinary HDE and (m,n) type HDE models in $f(G)$ gravity.

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